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CASSANDRA RICHARDS
ACTING TEAM LEADER
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Patents Act 1990

PROVISIONAL SPECIFICATION FOR THE INVENTION ENTITLED:

Pattern and Texture Orientation Estimator

Name and Address of Applicant:

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Names of Inventors:

Kieran Gerard Larkin
Michael Alexander Oldfield

This invention is best described in the following statement:

• •

PATTERN AND TEXTURE ORIENTATION ESTIMATOR

Technical Field of the Invention

The present invention relates generally to image processing and, in particular, to
5 the automatic estimation of pattern and texture orientation of an image.

Background Art

Images are often characterised by a number of features including pattern and texture. A number of image processing operations depend upon the estimation of the
10 orientation of these image features.

Image processing/analysis applications where the estimation of orientation is important include:

- edge orientation detection;
- orientation input to steerable filters;
- 15 • pattern analysis;
- texture analysis, where the local orientation of texture is estimated for characterisation purposes; and
- orientation selective filtering, processing, and enhancement of images.

One such area where the estimation of orientation is particularly important is the
20 demodulation of fringe patterns or equivalently, AM-FM modulated patterns. Examples of such patterns are illustrated in Figs. 2A and 5A. One area where such patterns exist is in fingerprint analysis. Other areas include the analysis of naturally formed patterns such as an iris diaphragm, ripples in sand, and fluid convection in thin layers. The primary reason why it is useful to know the fringe orientation when demodulating such a fringe
25 pattern is because it allows for 1-dimensional demodulators to be aligned correctly.

Another area where the estimation of pattern orientation is used is in image re-sampling and enhancement.

Known methods for estimating pattern orientation include gradient-based methods. A serious deficiency with such gradient-based methods is that at the ridges and
30 valleys of images, the gradient has zero magnitude. Gradient methods are therefore unable to provide information about pattern direction in such regions.

Disclosure of the Invention

It is an object of the present invention to substantially overcome, or at least ameliorate, one or more disadvantages of existing arrangements.

According to a first aspect of the invention, there is provided a method of estimating an orientation angle of a pattern in an image, said method comprising the steps of:

- 5 applying a complex energy operator to the image to provide an energy encoded image;
- determining a phase component of said energy encoded image; and
- calculating said orientation angle from said phase component of said energy
- 10 encoded image.

According to another aspect of the invention, there is provided an apparatus for implementing any one of the aforementioned method.

Brief Description of the Drawings

15 A preferred embodiment of the present invention will now be described with reference to the drawings, in which:

Fig. 1 is an illustration of the local structure of a fringe pattern;

Fig. 2A is an example of a fringe pattern image upon which the preferred embodiment of the invention can be applied;

20 Figs. 2B and 2C are the magnitude and phase components respectively of an intermediate result in applying an energy operator to the image of Fig. 2A;

Figs. 2D and 2E are the magnitude and phase components respectively of another intermediate result in applying the energy operator to the image of Fig. 2A;

25 Figs. 2F and 2G are the magnitude and phase components respectively of applying the energy operator to the image of Fig. 2A;

Fig. 3A is an example of a fringe pattern image containing noise, upon which the preferred embodiment of the invention can be applied;

Figs. 3B and 3C are the magnitude and phase components respectively of applying the energy operator to the image of Fig. 3A;

30 Figs. 3D and 3E are the magnitude and phase components respectively of applying a modified energy operator of the preferred embodiment of the invention to the image of Fig. 3A;

Fig. 4A is an example of a fringe pattern image containing noise, upon which the preferred embodiment of the invention can be applied;

Figs. 4B and 4C are the magnitude and phase components respectively of applying the energy operator to the image of Fig. 4A;

5 Figs. 4D and 4E are the magnitude and phase components respectively of applying the modified energy operator of the preferred embodiment of the invention to the image of Fig. 4A;

Fig. 5A is an example of a fringe pattern image with amplitude and frequency modulation, upon which the preferred embodiment of the invention can be applied;

Figs. 5B and 5C are the magnitude and phase components respectively of applying the energy operator to the image of Fig. 5A;

10 Figs. 5D and 5E are the magnitude and phase components respectively of applying the modified energy operator of the preferred embodiment of the invention to the image of Fig. 5A;

Fig. 6A is an example of a texture image, upon which the preferred embodiment of the invention can be applied;

15 Figs. 6B and 6C are the magnitude and phase components respectively of applying the energy operator to the image of Fig. 6A;

Figs. 6D and 6E are the magnitude and phase components respectively of applying the modified energy operator of the preferred embodiment of the invention to the image of Fig. 6A;

20 Fig. 7 is a schematic block diagram of a general purpose computer upon which an embodiment of the present invention can be practised; and

Fig. 8 is a flow diagram of a method according to the preferred embodiment of the invention.

♦♦

25 Detailed Description including Best Mode

In recent years, an efficient method of signal demodulation using a concept known as an "energy operator" has become popular. The operator can be used for demodulation of AM and FM signals, including combined AM-FM signals, using a result from the analysis of simple harmonic motion (SHM). The energy operator Ψ is defined
30 as:

$$\Psi \{f(x)\} = \left(\frac{\partial f}{\partial x} \right)^2 - f \frac{\partial^2 f}{\partial x^2} \quad (1)$$

A particularly useful property of the energy operator Ψ is that it gives uniform estimates of modulation parameters anywhere on the signal f . Essentially this is due to the fact that, at local peaks (and troughs) of the signal f , the energy is concentrated in the potential energy component, represented by the second term in Equation (1), whereas at the zero crossings, the energy is in the kinetic component represented by the first term in Equation (1). In other words, the rapidly varying sine and cosine components associated with AM-FM signals are exactly cancelled out by the energy operator Ψ , leaving an underlying constant representing total energy.

The operation of the energy operator Ψ has also been extended to N-dimensions. This is described in the publication "A multi-dimensional energy operator for image processing", SPIE Conference on Visual Communications and Image Processing, Boston, MA, [1992], 177-186, by P. Maragos, A.C. Bovik, and J. F. Quartieri, the contents of which are incorporated herein by cross reference.

Utilising the energy operator Ψ on images, (i.e. data sets formed in 2-dimensions,) separate x and y components may be calculated and added together to obtain an overall 2-dimensional energy operator.

However, the energy operator Ψ defined in this simple way has certain deficiencies. The main deficiency being that the orientation associated with the energy components is strictly limited to the positive quadrant of the x-y plane, which means that visually very different orientations are indistinguishable using two positive energy components.

Referring to Fig. 1, consider a 2-dimensional fringe pattern or AM-FM pattern, located around a point (x_0, y_0) and formed by a number of fringes 10 . The intensity of the fringe pattern can be represented as follows:

$$f(x,y) = b(x,y) \cdot \cos[2\pi(u_0\{x-x_0\} + v_0\{y-y_0\}) + \chi] \quad (2)$$

wherein any slowly varying (non-multiplicative) background offsets are removed with an appropriate high-pass filter. An amplitude modulation term is denoted by $b(x,y)$, which is assumed to be a slowly varying function. A small region of interest is defined by Ω . Within this small region Ω , the spatial frequency components u_0 and v_0 are slowly varying so that they are effectively constant around the point (x_0, y_0) , making the carrier a linear function of x and y . A normal 12 to the local fringes is at an angle β_0 to the x-axis. The local spatial frequency components u_0 and v_0 also satisfy the following Equations:

$$u_0^2 + v_0^2 = \sigma_0^2 \quad (3)$$

$$\sigma_0 = \frac{2\pi}{\lambda_0} \quad (4)$$

$$\tan(\beta_0) = \frac{v_0}{u_0} \quad (5)$$

wherein λ_0 is the fringe spacing.

The x and y component energy operators Ψ_x and Ψ_y respectively may be performed
5 on the fringe pattern defined in Equation (1) as follows:

$$\Psi_x \{f(x, y)\} = \left(\frac{\partial f}{\partial x} \right)^2 - f \frac{\partial^2 f}{\partial x^2} \approx (2\pi u_0 b)^2 \quad (6)$$

$$\Psi_y \{f(x, y)\} = \left(\frac{\partial f}{\partial y} \right)^2 - f \frac{\partial^2 f}{\partial y^2} \approx (2\pi v_0 b)^2 \quad (7)$$

Substituting Equations (6) and (7) into Equations (3) and (5), the local frequency
and orientation of the local fringe pattern may alternatively be expressed as follows:

$$\sigma_0^2 = \frac{\Psi_x \{f\} + \Psi_y \{f\}}{(2\pi b)^2} \quad (8)$$

$$\tan(\beta_0) = \pm \sqrt{\frac{\Psi_y \{f\}}{\Psi_x \{f\}}} \quad (9)$$

Equation (9) indicates a loss in sign information, which corresponds to an inability
to distinguish between fringes at four different orientations $\beta_0, -\beta_0, \pi + \beta_0, \pi - \beta_0$. This
is very undesirable because the human eye can clearly separate β_0 from $\pi - \beta_0$, and $-\beta_0$
15 from $\pi + \beta_0$. In general, however, it is not possible to distinguish (on a local level at
least) between any orientation and the π rotated orientation.

An alternative approach to extending the energy operator Ψ to two dimensions is by
defining a two dimensional complex operator Ψ_c which encodes the energy in the
magnitude and the orientation in the phase:

$$\Psi_x \{f\} + \Psi_y \{f\} = (2\pi b)^2 (u_0^2 + iv_0^2) \quad (10)$$

As mentioned above, the simple x and y components alone fail to represent the orientation correctly. A preferable approach would be to have a 2D energy operator that has the following output:

$$\Psi_c \{f\} = (2\pi b)^2 (u_0 + iv_0)^2 = (2\pi\sigma_0 b)^2 \exp(2i\beta_0) \quad (11)$$

5 The complex energy operator Ψ_c enables the isolation of the fringe spacing λ_0 , as seen in Fig. 1, and orientation angle β_0 respectively. It is noted that the term 2 in the exponential factor of Equation (11) again causes the orientation angle β_0 to be defined modulo π . Such an energy operator is developed by defining a 2- dimensional complex differential operator D as follows:

$$10 \quad D\{f\} = \frac{\partial f}{\partial x} + i \frac{\partial f}{\partial y} \quad (12)$$

The complex energy operator Ψ_c can then be defined as follows:

$$(D\{f\})^2 - fD^2\{f\} = (2\pi\sigma_0 b)^2 \exp(2i\beta_0) = \Psi_c \{f\} \quad (13)$$

With the Fourier transform defined as follows:

$$F(u, v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) \exp[-2\pi i(ux + vy)] dx dy \quad (14)$$

15 the operator D can be implemented in the Fourier space , providing the following relationship:

$$(2\pi i)(u + iv)F(u, v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} D\{f(x, y)\} \exp[-2\pi i(ux + vy)] dx dy \quad (15)$$

wherein

$$2\pi(u + iv) \equiv 2\pi q \cdot \exp(i\varphi) \quad (16)$$

20 and the polar coordinate transforms are:

$$\left. \begin{aligned} u &= q \cos(\varphi) \\ v &= q \sin(\varphi) \\ u^2 + v^2 &= q^2 \end{aligned} \right\} \quad (17)$$

The corresponding Fourier operation of Equation (15) provides for the multiplication of the Fourier transform of the fringe pattern $F(u, v)$ with a spiral phase

filter, $q \exp(i\phi)$. The spiral phase filter has the characteristic of linearly (conical) increasing in magnitude with frequency. The Fourier transformation pairs may be written as:

$$F(u, v) \Leftrightarrow f(x, y) \quad (18)$$

$$5 \quad (2\pi i) q \exp(i\phi) F(u, v) \Leftrightarrow D\{f(x, y)\} \quad (19)$$

$$(2\pi i)^2 q^2 \exp(2i\phi) F(u, v) \Leftrightarrow D^2\{f(x, y)\} \quad (20)$$

The derivatives in Equation (13) can therefore be implemented as 2-dimensional Fourier filters with spiral phase and conical magnitude.

By applying the differential operators defined in Equations (18) to (20) as filters
10 through simple multiplication of the image of Fig. 2A, the results as shown in Figs. 2B to 2G is obtained. Figs. 2B and 2C show the magnitude and phase components respectively of the $(D\{f\})^2$ term of Equation (13), calculated by using the relationship in Equation (19). Similarly, Figs. 2D and 2E show the magnitude and phase components respectively of the $fD^2\{f\}$ term of Equation (13), calculated by using the relationship in Equation (20).
15 The magnitude and phase components respectively of the complex energy operator Ψ_c is shown in Figs. 2F and 2G. Referring to Equation (11), the phase component of the complex energy operator Ψ_c has double the orientation angle β_0 of the fringe pattern f .

All the above calculations and derivations may alternatively be implemented as convolution operators without Fourier transformation.

20 However, when the energy operator Ψ_c is applied to a fringe pattern f containing noise, such as that shown in Fig. 3A, the resulting magnitude and phase components of the complex energy operator Ψ_c , shown in Figs. 3B and 3C, are less satisfactory. The primary reason for the degradation is the linear (conical) spectral enhancement of the differential operator D . The differential operator D effectively enhances high frequency
25 noise, as it essentially operates as a high-pass filter. In particular, in the areas of low spatial frequency σ_0 , such as the area 20 on Fig. 3A, the contribution by the noise signal due to the differentiation dominates the determination of the orientation of the fringe pattern. Referring to Fig. 3C, the phase component, from which the orientation can be obtained by using the relationship from Equation (11), provides near random noise in the
30 corresponding area 22.

One possible correction is to apply a low pass filter function to the input image or the result. However, the energy operator Ψ is not a linear (shift invariant) operator. It is dependent on products of the input function f and its derivatives $\partial f/\partial x$ and $\partial^2 f/\partial x^2$, as can be seen from Equation (1). Low pass filtering results in the image becoming blurred.

5 To overcome the deficiencies of the complex energy operator Ψ_c , while maintaining the ease of calculation of the orientation angle β_0 , according to the preferred embodiment, a pure phase operator D_M , thus having uniform (spectral) magnitude, is created by setting q in Equations (19) and (20) to unity, to define the following Fourier transform pair:

$$\exp(i\varphi)F \Leftrightarrow D_M \{f(x, y)\} \quad (21)$$

10 The pure phase operator D_M is a spiral phase (or vortex) operator which results in the removal of noise without a blurring of the signal. By applying the modified energy operator Ψ_M defined as:

$$\Psi_M \{f\} = (D_M \{f\})^2 - f D_M^2 \{f\} \quad (22)$$

15 to the image in Fig. 3A, the magnitude and phase components respectively of the modified energy operator Ψ_M shown in Figs. 3D and 3E, are obtained. The comparison of the phase components of the complex energy operator Ψ_c shown in Fig. 3C and modified energy operator Ψ_M shown in Fig. 3E, and in particular to the corresponding areas 22 and 24 respectively, indicate that the modified energy operator Ψ_M provides a better result.

20 It is noted that, similar to the energy operator Ψ , the modified energy operator Ψ_M is also non-linear. A consequence of this is that it is generally not possible to obtain the performance of the modified energy operator Ψ_M by merely applying a low pass filter to the input function, nor by filtering the output function, of the energy operator Ψ .

25 The modified energy operator Ψ_M has a property of scale invariance, which it inherits from the scale invariant D_M operator. Scale invariance is another aspect of the operator's spectral neutrality and means that the operator essentially gives outputs independent of feature size.

30 To further illustrate the advantages of the modified energy operator Ψ_M , the complex energy operator Ψ_c and the modified energy operator Ψ_M are respectively applied to an image with uniform noise in the range ± 64 greylevels shown in Fig. 4A. The magnitude and phase components respectively of the complex energy operator Ψ_c are

shown in Figs. 4B and 4C, while the magnitude and phase components respectively of the modified energy operator Ψ_M are shown in Figs. 4D and 4E. Because of the high level of noise in the input image, the phase component of the complex energy operator Ψ_c is completely weighed down by the contribution of the noise. The modified energy operator Ψ_M gives a much clearer phase without any obvious blurring that would be expected of noise reduction by conventional low pass filtering of the complex energy operator Ψ_c .

Another comparative example wherein the performance of the modified energy operator Ψ_M can be seen is shown in Figs. 5A to 5E. Fig. 5A shows an amplitude and frequency modulated image. The magnitude and phase components respectively of the complex energy operator Ψ_c are shown in Figs. 5B and 5C, while the magnitude and phase components respectively of the modified energy operator Ψ_M are shown in Figs. 5D and 5E. The complex energy operator Ψ_c again has difficulty in regions of low spatial frequency λ_0 , such as area 30, causing the corresponding area 32 in Fig. 5C to have high levels of uncertainty. On the other hand, the corresponding area 34 when the modified energy operator Ψ_M is applied, provides a much clearer result.

It is further noted that since the underlying fringe pattern of the images in Figs. 3A, 4A and 5A are the same with different processes applied thereto, the processes not affecting the orientation of the fringes of the underlying pattern, the results of the modified energy operator Ψ_M shown in Figs. 3E, 4E and 5E are substantially similar.

The modified energy operator Ψ_M may be implemented entirely in the Fourier space domain by using complex convolution kernels that correspond to the pure phase spirals. With the kernel k and its Fourier transform K , the Fourier transform pair can be defined as:

$$K(u, v) = \exp(i\varphi) = \frac{u + iv}{q} \Leftrightarrow \frac{i(x + iy)}{2\pi r^3} = \frac{i \exp(i\theta)}{r^2} = k(x, y) \quad (23)$$

wherein the spatial polar coordinates satisfy the following:

$$\left. \begin{aligned} x^2 + y^2 &= r^2 \\ x &= r \cos(\theta) \\ y &= r \sin(\theta) \end{aligned} \right\} \quad (24)$$

The convolution kernel k reduces by the inverse square of the radius, and also has a spiral phase structure, but rotated by 90° with respect of the x-y coordinates. According to the above, since it is now known those operations required to be performed to extract

local orientation information from a fringe pattern, it is not necessary to perform such calculations in the Fourier domain. Rather, the desired functions may be recalculated in the real domain thereby facilitating ease of processing. In many cases the desired functions may be approximated by suitably truncated kernels. The inverse square drop-off allowing relatively small truncation errors even for small kernels

Referring again to Fig. 1, by considering a sufficiently small region Ω of images composed of line or edge features, the local structure fits the model of Equation (2). This is true for many image features, the most obvious exceptions being textures that contain multiple AM-FM modulated signals. Sometimes an image may approximate the model of Equation (2) except for a low or zero frequency background offset in intensity. In such cases this background level may be removed by high pass filtering (or related methods) leaving an image that does satisfy Equation (2) which can then be processed using the complex energy operator formalism.

Where Equation (2) is representative, the modified energy operator Ψ_M , as defined in Equation (22), to be used for the calculation of the orientation angle β_0 of all such images.

An example of such an image and the operation of the modified energy operator Ψ_M are shown in Figs. 6A to 6E. Fig. 6A shows a texture image. The texture image is characterised by distinct lines and areas of low variation. The magnitude and phase components respectively of the complex energy operator Ψ_c are shown in Figs. 6B and 6C, while the magnitude and phase components respectively of the modified energy operator Ψ_M are shown in Figs. 6D and 6E. The phase component of the modified energy operator Ψ_M provides a result that is more intuitively representative of the orientation of the texture image of Fig. 6A.

A flow diagram of a method of estimating the pattern and texture orientation of images is shown in Fig. 8. An input image is inserted in step 200. The input image is typically digital format with a predetermined number of columns and rows. Alternatively the image may be scanned to convert it into the digital format.

Although the preceding analysis has been in terms of continuous functions and continuous operations, the analysis is also directly applicable to discretely sampled functions (images) and discrete operations.

A Fourier transform of the image is calculated in step 210; typically using the Fast Fourier Transform (FFT). The Fourier transformed image is multiplied with a term $\exp(i\phi)$ in step 220.

5 An output of step 220 is again multiplied with the term $\exp(i\phi)$ in step 230 before it is inverse Fourier transformed, typically using an Inverse Fast Fourier Transform (IFFT) in step 240. The result is then multiplied with the input signal in step 270.

The output from step 220 is also inverse Fourier transformed in step 250 before it is squared in step 260. The output from step 270 is subtracted from the output of step 260 in step 280. From this complex signal, the angle of the signal is calculated in step 290
10 before it is halved in step 300 to provide an orientation angle β_0 as an output in step 310.

The method of estimating the pattern and texture orientation of images is preferably practiced using a conventional general-purpose computer system 100, such as that shown in Fig. 7 wherein the calculation of the orientation angle β_0 may be implemented as software, such as an application program executing within the computer
15 system 100. In particular, the calculation may be effected by instructions in the software that are carried out by the computer. The software may be stored in a computer readable medium, including the storage devices described below. The software is loaded into the computer from the computer readable medium, and then executed by the computer. A computer readable medium having such software or computer program recorded on it is a
20 computer program product. The use of the computer program product in the computer preferably effects an advantageous apparatus for demodulating two-dimensional fringe patterns in accordance with the embodiments of the invention.

The computer system 100 comprises a computer module 102, input devices such as a keyboard 110 and mouse 112, output devices including a printer 108 and a display
25 device 104.

The computer module 102 typically includes at least one processor unit 114, a memory unit 118, for example formed from semiconductor random access memory (RAM) and read only memory (ROM), input/output (I/O) interfaces including a video interface 122, and an I/O interface 116 for the keyboard 110 and mouse 112. A storage
30 device 124 is provided and typically includes a hard disk drive 126 and a floppy disk drive 128. A magnetic tape drive (not illustrated) may also be used. A CD-ROM drive 120 is typically provided as a non-volatile source of data. The components 114 to 128 of the computer module 102, typically communicate via an interconnected bus 130 and in a manner which results in a conventional mode of operation of the computer

system 100 known to those in the relevant art. Examples of computers on which the embodiments can be practised include IBM-PC's and compatibles, Sun Sparcstations or alike computer systems evolved therefrom.

Typically, the application program of the preferred embodiment is resident on
5 the hard disk drive 126 and read and controlled in its execution by the processor 114. Intermediate storage of the program may be accomplished using the semiconductor memory 118, possibly in concert with the hard disk drive 126. In some instances, the application program may be supplied to the user encoded on a CD-ROM or floppy disk and read via the corresponding drive 120 or 128, or alternatively may be read by the user
10 from a network via a modem device (not illustrated). Still further, the software can also be loaded into the computer system 100 from other computer readable medium including magnetic tape, a ROM or integrated circuit, a magneto-optical disk, a radio or infra-red transmission channel between the computer module 102 and another device, a computer readable card such as a PCMCIA card, and the Internet and Intranets including email
15 transmissions and information recorded on websites and the like. The foregoing is merely exemplary of relevant computer readable mediums. Other computer readable mediums may be practiced without departing from the scope and spirit of the invention.

The calculation of the orientation angle β_0 may alternatively be implemented in dedicated hardware such as one or more integrated circuits performing the functions or
20 sub functions of the calculation. Such dedicated hardware may include graphic processors, digital signal processors, or one or more microprocessors and associated memories.

♦ ♦

The Claims defining the invention are as follows:
Claims:

1. A method of estimating an orientation angle of a pattern in an image, said method comprising the steps of:

5 applying a complex energy operator to the image to provide an energy encoded image;

 determining a phase component of said energy encoded image; and

 calculating said orientation angle from said phase component of said energy encoded image.

10

2. A method as claimed in claim 1 wherein said complex energy operator being defined as:

$$\Psi_c \{f\} = (D \{f\})^2 - fD^2 \{f\}$$

and said phase component of said energy encoded image being defined as:

15 $2\beta_0 = \arg(\Psi_c \{f\})$

3. A method as claimed in claim 1 wherein said complex energy operator being a modified complex energy operator defined as:

$$\Psi_M \{f\} = (D_M \{f\})^2 - fD_M^2 \{f\}$$

20 and said phase component of said energy encoded image being defined as:

$$2\beta_0 = \arg(\Psi_M \{f\})$$

25

4. A method as claimed in any one of claims 1 to 3 wherein said image is preprocessed to remove background offsets.

5. Apparatus for estimating an orientation angle of a pattern in an image, said apparatus comprises:

 means for applying a complex energy operator to the image to provide an energy encoded image;

30 means for determining a phase component of said energy encoded image; and

 means for calculating said orientation angle from said phase component of said energy encoded image.

6. Apparatus as claimed in claim 1 wherein
said complex energy operator being defined as:

$$\Psi_c \{f\} = (D \{f\})^2 - fD^2 \{f\}$$

and said phase component of said energy encoded image being defined as:

5 $2\beta_0 = \arg(\Psi_c \{f\})$

7. Apparatus as claimed in claim 1 wherein
said complex energy operator being a modified complex energy operator defined as:

$$\Psi_M \{f\} = (D_M \{f\})^2 - fD_M^2 \{f\}$$

10 and said phase component of said energy encoded image being defined as:

$$2\beta_0 = \arg(\Psi_M \{f\})$$

8. Apparatus as claimed in any one of claims 6 to 8, said apparatus further
comprising a means for preprocessing said image to remove background offsets.

15

9. A method of estimating an orientation angle of a pattern in an image, said
method being substantially as described herein with reference to the drawings.

10. Apparatus for estimating an orientation angle of a pattern in an image, said
20 apparatus being substantially as described herein with reference to the drawings.

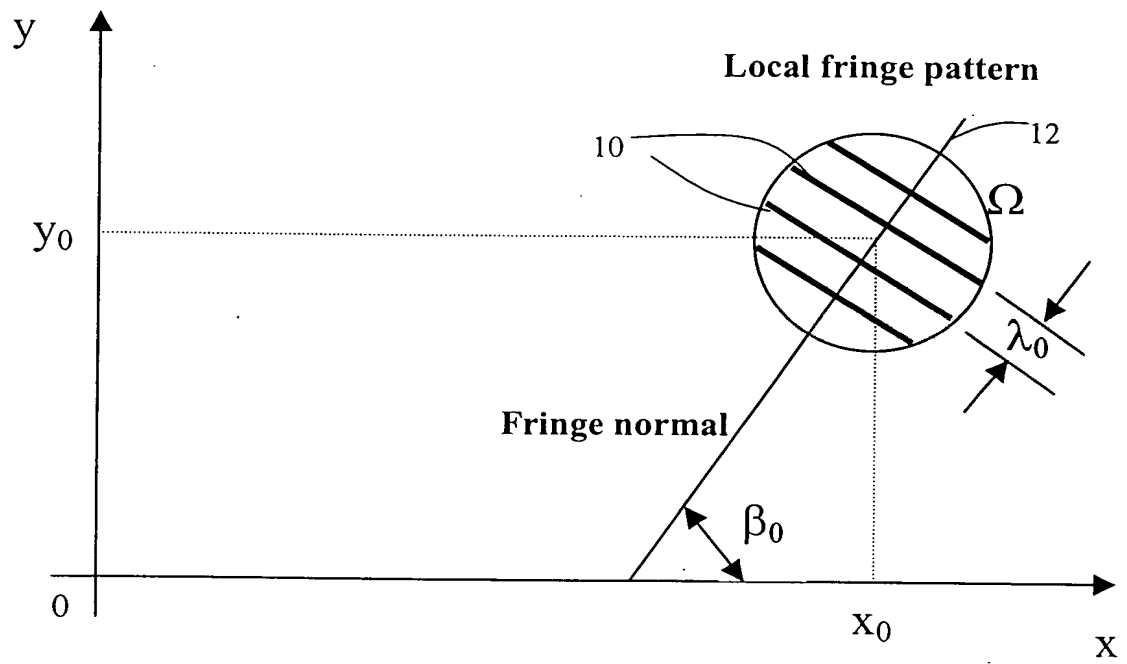
DATED this Fourteenth Day of April, 2000

Canon Kabushiki Kaisha

Patent Attorneys for the Applicant

SPRUSON & FERGUSON

25



5

Fig. 1

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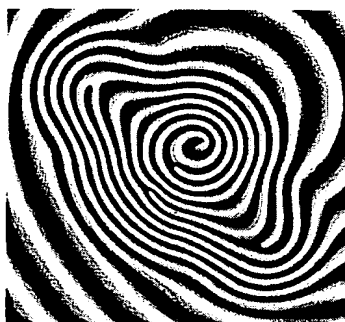


Fig. 2A

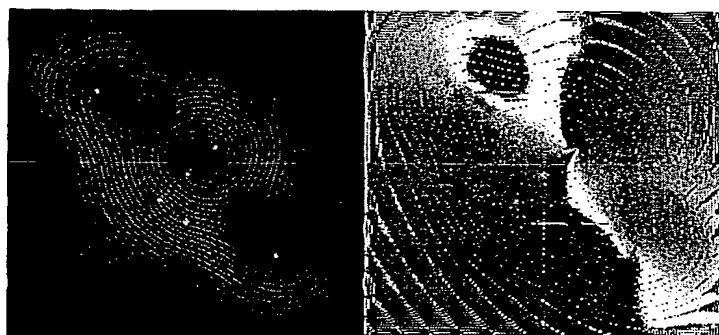


Fig. 2B

Fig. 2C

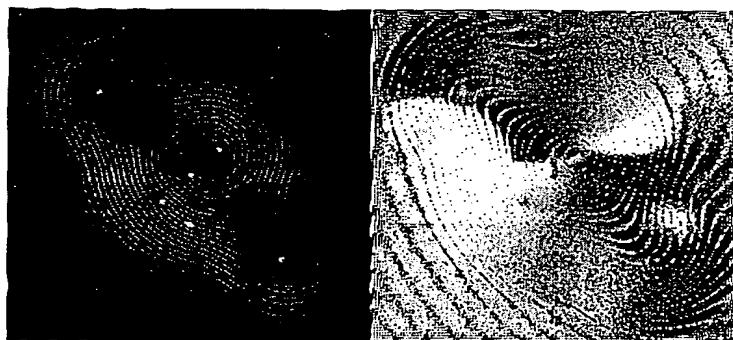


Fig. 2D

Fig. 2E

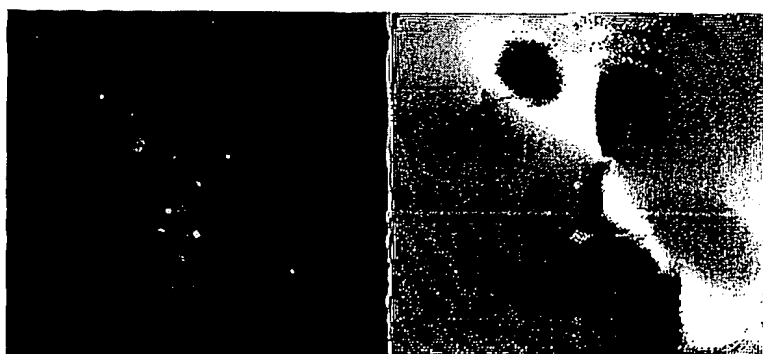


Fig. 2F

Fig. 2G

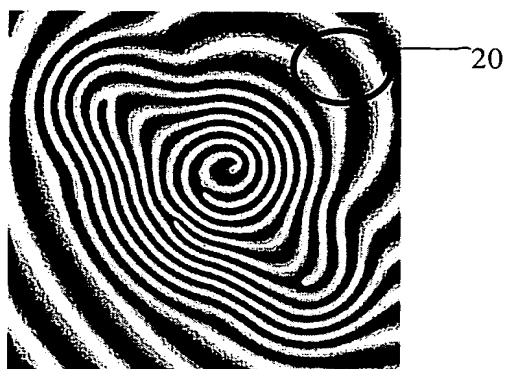


Fig. 3A

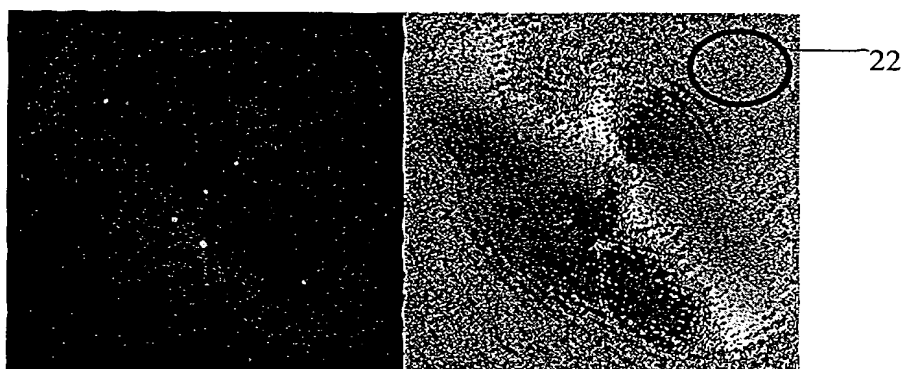


Fig. 3B

Fig. 3C



Fig. 3D

Fig. 3E

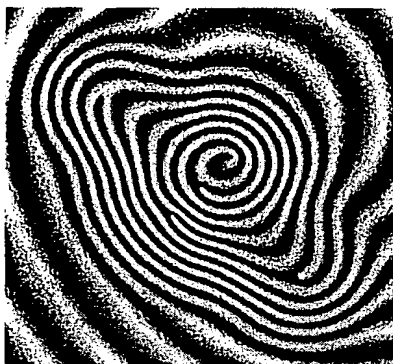


Fig. 4A

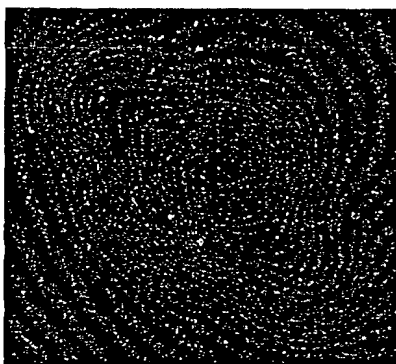


Fig. 4B

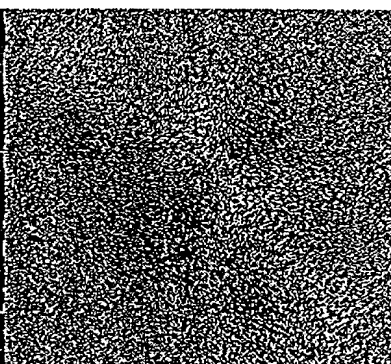


Fig. 4C

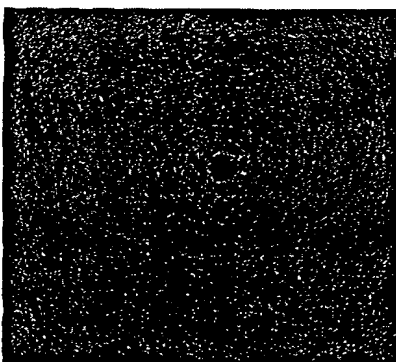


Fig. 4D

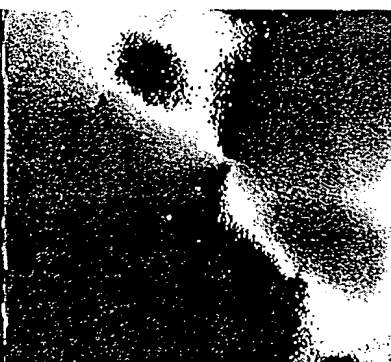


Fig. 4E

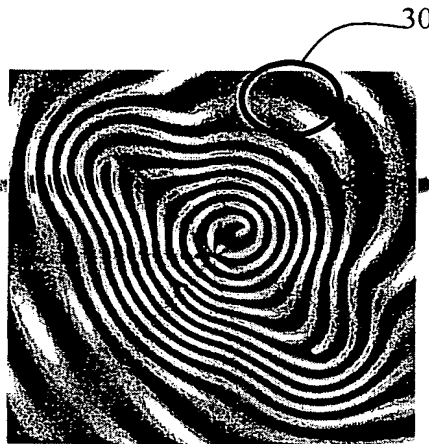


Fig. 5A

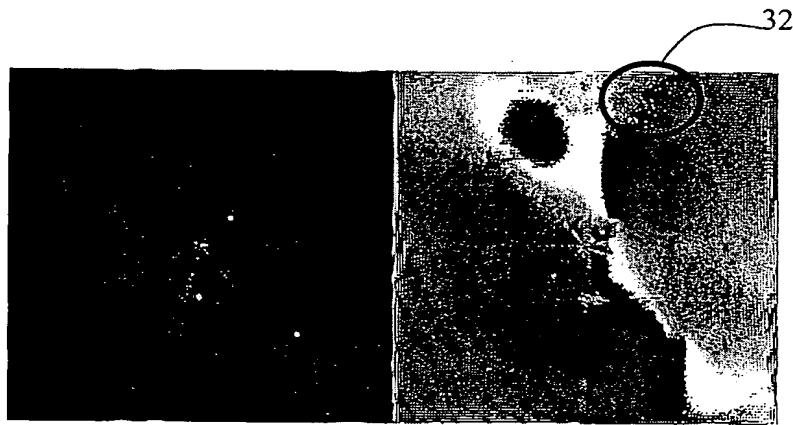


Fig. 5B

Fig. 5C



Fig. 5D

Fig. 5E.

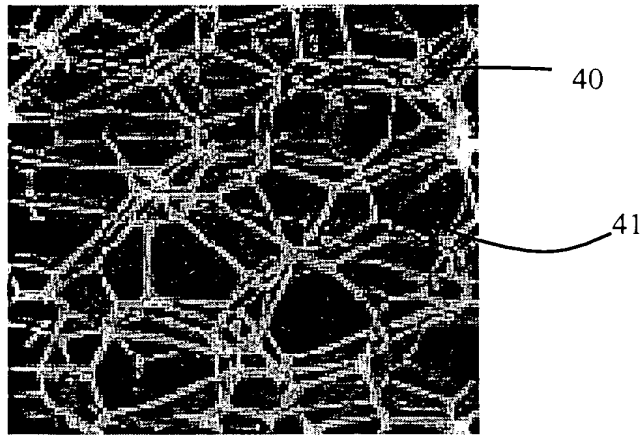


Fig. 6A

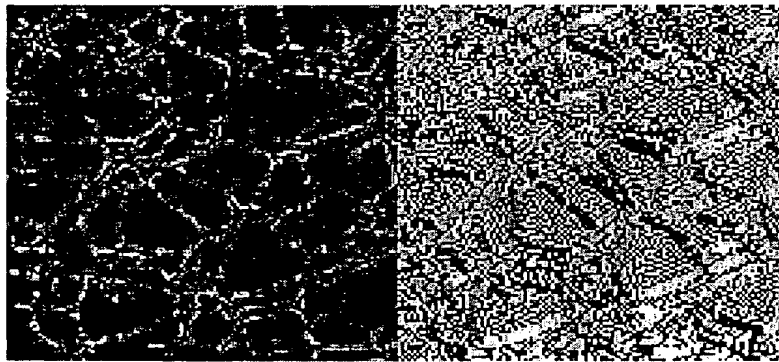


Fig. 6B

Fig. 6C

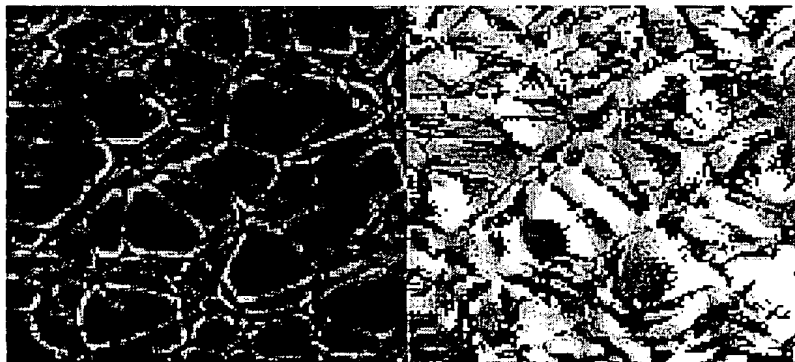


Fig. 6D

Fig. 6E.

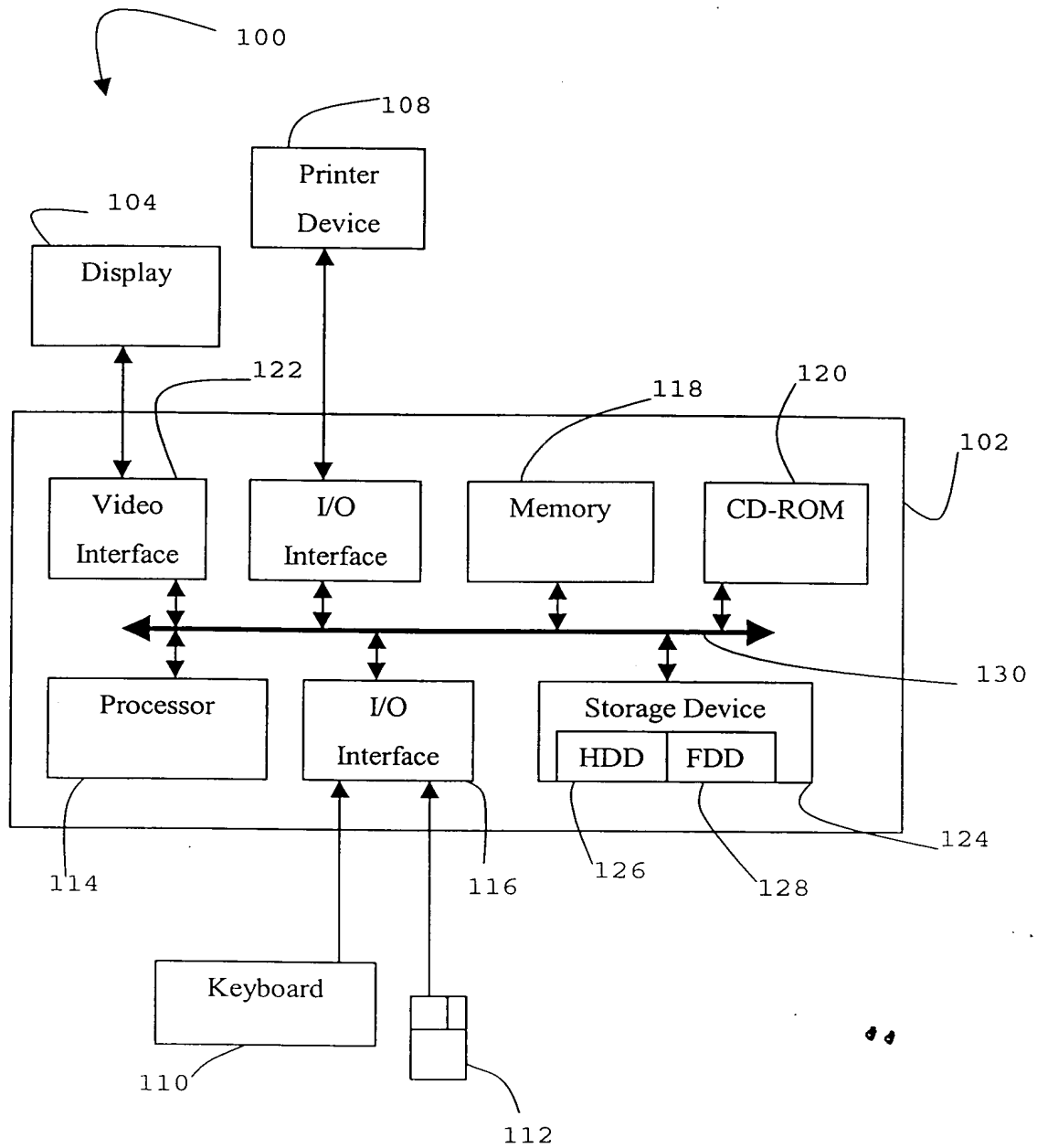


Fig. 7

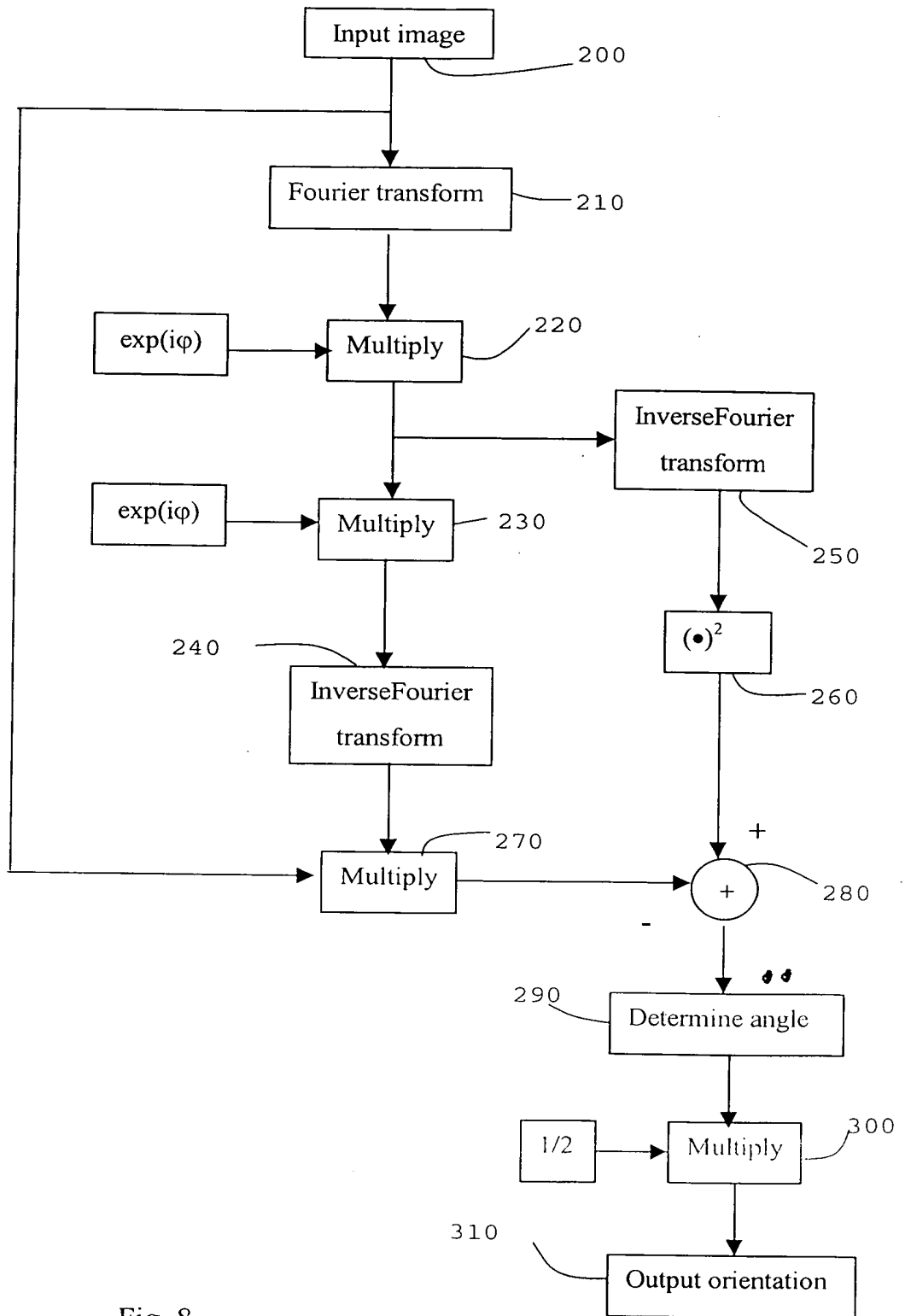


Fig. 8

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